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Thermal Analysis on Al-Si Piston Using Different Heat Barrier Coatings

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ABSTRACT

The objective of the present work is to focus on the thermal analysis of ceramic coated piston, working under thermal loads. Thermal analysis was carried out on uncoated and ceramic coated piston to verify the temperature changes at the ceramic coated regions using Hyper-mesh and Ansys. The study of thermal stresses generated due to temperature differences at different materials junctions used in coating was analyzed.

Keywords: Ceramic Coatings, IC engine, Thermal barrier

1. INTRODUCTION

It is very important to calculate the piston temperature to control the thermal stresses and deformations within acceptable levels. The temperature distribution enables us to optimize the thermal aspects of the piston design at lower cost, before the first prototype is constructed. As much as 60% of the total engine mechanical power lost is generated by piston ring assembly [1]. The piston is one among the most critical components of engines, reciprocating pumps, among other similar mechanisms and heavily-loaded under thermal conditions during the operations of an internal combustion engine (ICE). It is the continuous moving component that is contained by a cylinder and is made gas-tight by piston rings. The purpose of it is to make use of force like pressure up to 10 MPa, by transferring thermal effects due to temperatures up to 2,500 ˚C from expanding gas during the thermodynamic cycle processes in the cylinder via piston rod and/or connecting rod [2]. For proper functioning of the internal combustion diesel engine, accurate piston temperatures and the variations throughout the piston at whatever operating conditions are mandatorily required because piston temperatures influence on ignition process, delay in burning the air-fuel mixture at high compression ratio, ignition rate, thermal efficiency, and pollutants formation from the burnt gases. In between because of this processes, the heat is generated and gets transferred through medium in the form of conduction being solid, convection due to interaction with air which is fluid etc. It is important to maintain the durability of engine along with the topological connected components like piston, piston rings, valves, and cylinder wall, to avoid engine body damage and to improve engine design related to weight and auxiliary energy consumption.

2. MATERIALS

2.1 Conventional piston material

Pistons are commonly made out of a cast aluminium alloy among so many alloys for their low density with low mass and excellent thermal conductivity capabilities made from die or gravity casting process of manufacturing which is low in cost and having high structural integrity. The less mass of aluminium reduces the effect of inertial force and will help in initiating and maintaining acceleration of the piston such that the force can be utilized to power the application that is for the mechanical work. Among aluminium there are various types i.e., difference in composition of material in alloy form like Al-Si (aluminium-silicon) came into existence. Among these, mostly two kinds of Silicon are used in Aluminum alloy. They are eutectic kind of material with 12% and hypereutectic with 22%. If the amount of silicon content is not less than 12%, the material becomes brittle otherwise, it is ductile having elastic properties. Many alloys are now-a-days in the market available with different silicon compositions are mostly less than or equal to 12%. There are some manufacturers use cast iron for the manufacturing of piston [3].

2.2 Ceramic coatings

Thermal barrier coatings act as the insulators on piston surface making it possible to avail more heat for combustion resulting in better work done on piston. These coatings distribute the heat more evenly, which help in preventing high temperatures zones. Keeping more heat on to the piston surface rather than transferring prevents the pre-ignition. The problem in the combustion chamber with conventional materials is that most of the heat generated in an engine will be lost through heat transfer. Hence, the solution is to make the components insulate and withstand high temperatures in the combustion chamber. By TBCs, burning of gases in an engine can be done more efficiently by raising the temperature of the air-fuel mixture. Ceramic Coatings are used as a guarded covering on or amidst the engine parts, which result in lessening of rubbing, increase wear resistance and upgrade warm ensuring. Each one of these components have detectable effect on the execution parameters and the section life in a vehicle. These coatings help the fragments with cooperating in more uniform and greater outline. In publicize there are various warm limit covering like NiCrAl, TiCN, ZrO2, pottery coatings etc. These warm limit coatings are secured on the best piece of chamber to diminish the glow which finally decreases the temperatures inside the cylinder

3. DESIGN OF PISTON

3.1. Procedure for piston design

The design a piston we require some geometrical dimensions like piston height, diameter of piston crown, skirt length, piston rings radius etc. The following are the mathematical calculations one has to make use to properly design a piston having some known parameters. The procedure for piston designs consists of the following steps [4]**:**

- Thickness of head (**Error! Reference source not found.**)
- Heat flows through the piston head (H)
- Radial thickness of the ring (**Error! Reference source not found.**)

- Axial thickness of the ring (**Error! Reference source not found.**)
- Width of the top land (b1)
- Width of other ring lands (b2)

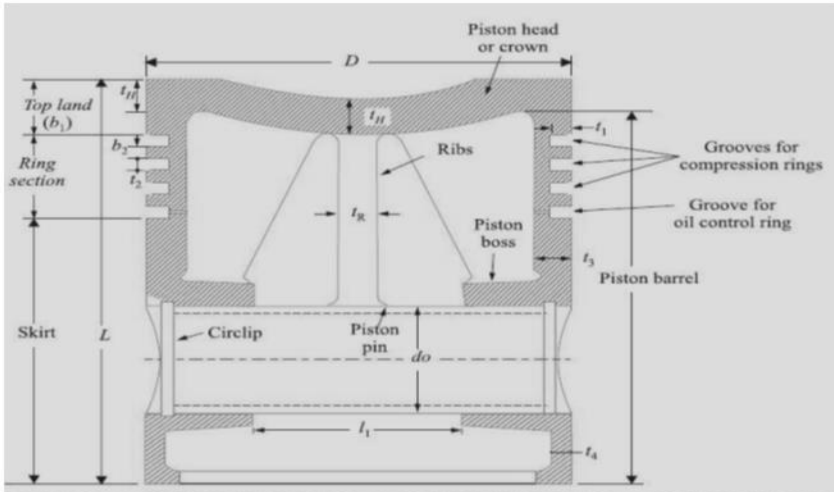

Fig.1 Schematic Description of Piston

Thickness of Piston Head (t_H)

The thickness of piston head is calculated using the following Grashoff's formula,

$$t_H = \sqrt{(3pD^2/(16\sigma_t)}$$

Where,

P= Maximum pressure in N/mm²

D= Cylinder bore/outside diameter of the piston in mm.

σ_t= Tensile stress for the material of the piston.

Here the material is a particular grade of AL-Si alloy whose permissible stress is 50 MPa-90Mpa. Before calculating thickness of piston head, the diameter of the piston has to be specified. The piston size that has been considered here has an L*D specified

Thickness of Ring (t_1) radially

t_1 = D□3p_w/□t

Where D = cylinder bore in mm

p_w= pressure of fuel on cylinder wall in N/mm². Its

value is limited from 0.025N/mm²

to 0.042N/mm². For present material, σ_t is 90Mpa

Thickness of Ring (t_2) axially

The thickness of the rings may be taken as t_2= 0.7 $t_1$to t_1

Let assume t_2 =5mm

Minimum axial thickness (t_2)= D/(10*n_r)

Where, n_r= number of rings

Top land width (b1)

The width of the top land varies from

b1 = t_H to 1.2t_H

Other lands Width (b2)

Width of other ring lands varies from

b2 = 0.75t_2 to t_2

Maximum Thickness of Barrel (t_3)

t_3 = 0.03*D + b + 4.5 mm

Where, b = depth of piston ring groove radially

Thus, the dimensions for the piston are calculated and these are used for modelling the piston in CATIA.

Table 1 Geometrical Dimensional Ranges of Piston [5]

S. No.	Description	Size Ranges Measurements(mm)
1	Cylinder bore, D	Between 135 to 145
2	Width of land	6.5 to 14.5
3	Height of piston, H	113 to 181
4	Distance from top of axis of piston pin, h1	62 to 65
5	Diameter of thickness of piston pin, d	42 to 70
6	Distance from the front of the first channel, e	8.5 to 16.5
7	Wall thickness between channels, h_a	4.2 to 7
8	Radial thickness of piston ring, t(r)	4.5 to 6.5
9	Axial thickness of piston ring, t(a)	4.5 to 6.5

Table 2: Geometrical Dimensions of Piston [6]

S. No	Description	Measurement(mm)
1	Length of Piston	67.002
2	Cylinder diameter or bore diameter of piston	93.04
3	Length between piston crown to piston inner	7.833
4	Thickness of piston liner	2
5	Ring portion groove height	4
6	Ring portion groove width	4
7	Number of rings	3

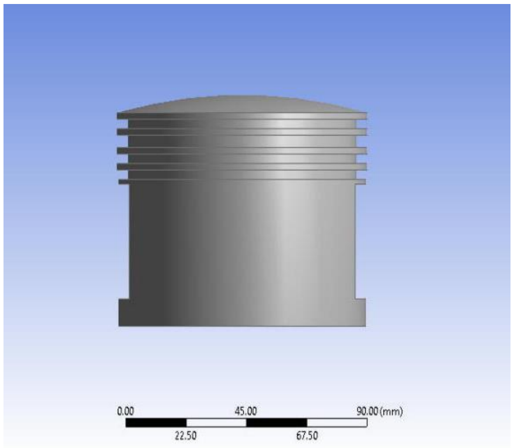

Fig. 2 Piston geometry without Thermal coating

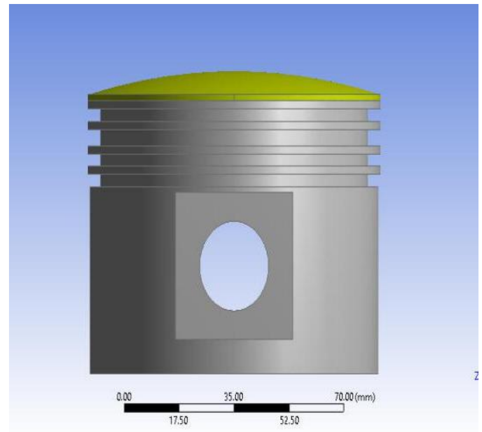

Fig.3 Piston geometry with thermal coating of 1.5mm thickness

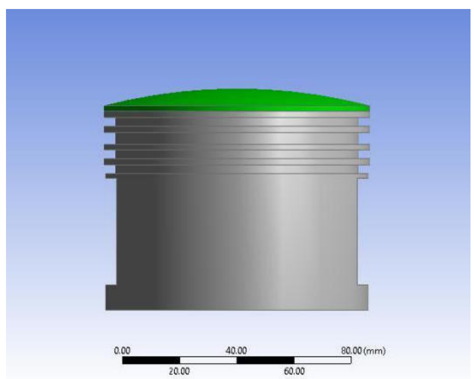

Fig. 4 Piston geometry with thermal coating of 2.0mm thickness

4. THERMAL ANALYSIS OF PISTON

Table 3: Materials & their Properties [7]

S. No.	Component	Material	Density Kg/m^3	Thermal conductivity(K)in W/m-˚C	Specific Heat in J/kg-K
1	Piston	Al-Si	2937	197	894
2	Coating 1	BondCoating (NiCrAl)	7870	6.1	764
3	Coating 2	YSPZ	5650	1.4	620
4	Coating 3	Ceramic (MgZrO3)	5600	0.8	580

5. MESHING OF PISTON

Meshing is implying the process of discritizing the piston into number of small elements connected with nodes i.e., converting the physical geometrical model into the mathematical model. Here for piston, the meshing is done using the 3D- tetra elements. The component piston is finely meshed wherever required like the ring groove portion to acquire the most approximate solution. The mesh strategy is used for all the conditions in this analysis

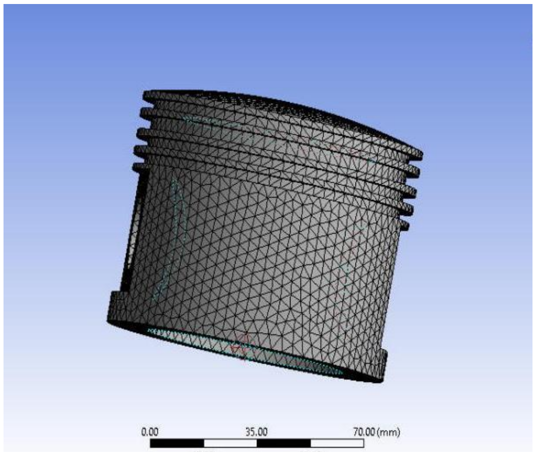

Fig.5 Mesh on piston without thermal coating

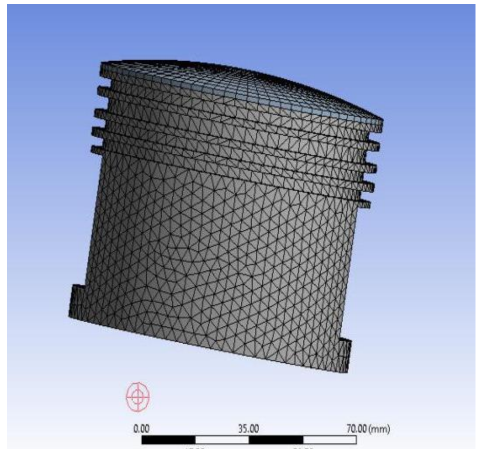

Fig.6 Mesh on piston with thermal coating of 1.5mm thickness

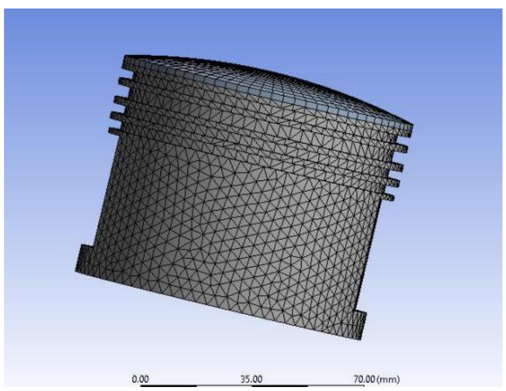

Fig.7 Mesh on piston with thermal coating of 2.0 mm thickness

Table 4 Meshing Statistic

S. No	Description	Number of Elements	Number of Nodes
1	Piston only	39860	9109
2	Piston with 1.5mm thickness coating	40098	10880
3	Piston with 2mm thickness coating	40008	10848

6. THERMAL BOUNDARY CONDITIONS

The load inputs in the form of temperatures and the constraints as heat transfer coefficient. Both together are considered as the boundary conditions. Applying these boundary conditions indirectly we are creating the thermal environment on the piston. By applying these boundary conditions, the software understands the inputs and solves the mathematics involved to find the unknown variable

Table 5: Boundary Conditions [8]

S. No	Description	Temperature(˚C)	Heat Transfer coefficient(h) in W/m^2-K
1	On Piston Crown	960	2375
2	Between Piston crown and Liner	765	80
3	1st Ring portion	385	4000
4	Between 1st ring and 2nd ring	510	790
5	2nd Ring portion	380	3500
6	Between 2nd ring and 3rd ring	530	790
7	3rd Ring portion	350	3000
8	Underside of Crown	750	80
9	Piston Skirt outside	790	348
10	Piston Skirt inside	353	80

7. POST-PROCESSING

7.1. Case 1: Al-Si Piston without thermal coating

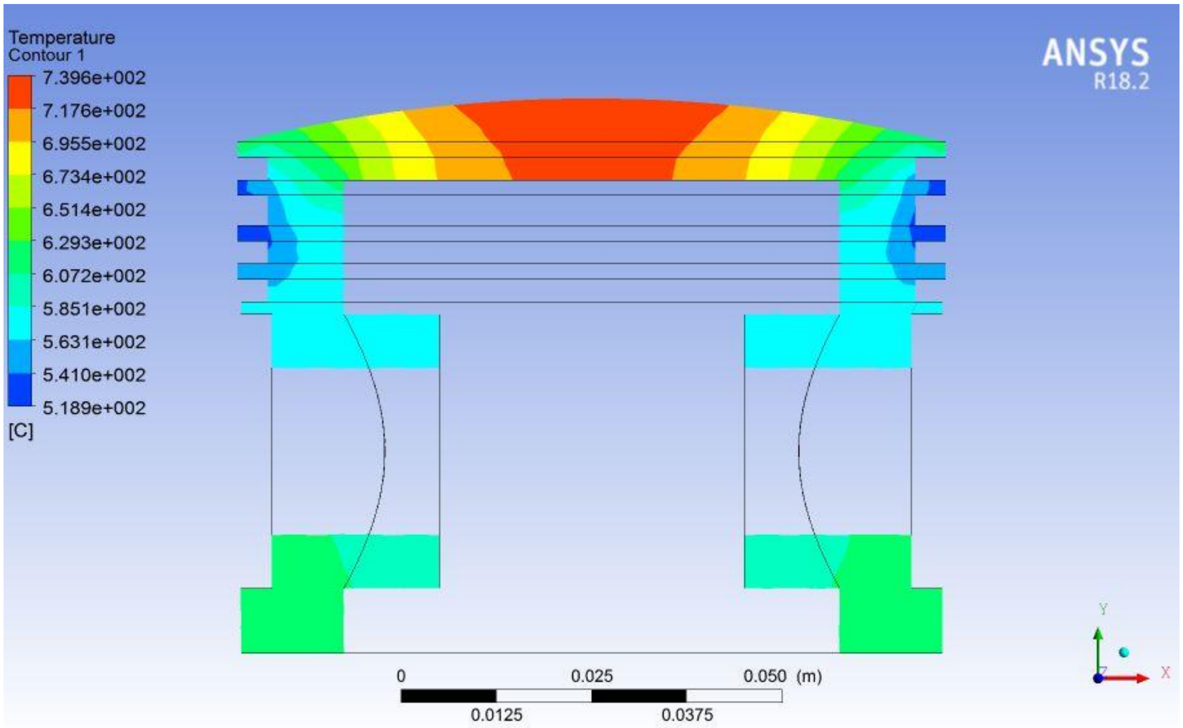

Fig.8 Temperature contour of piston without thermal coating

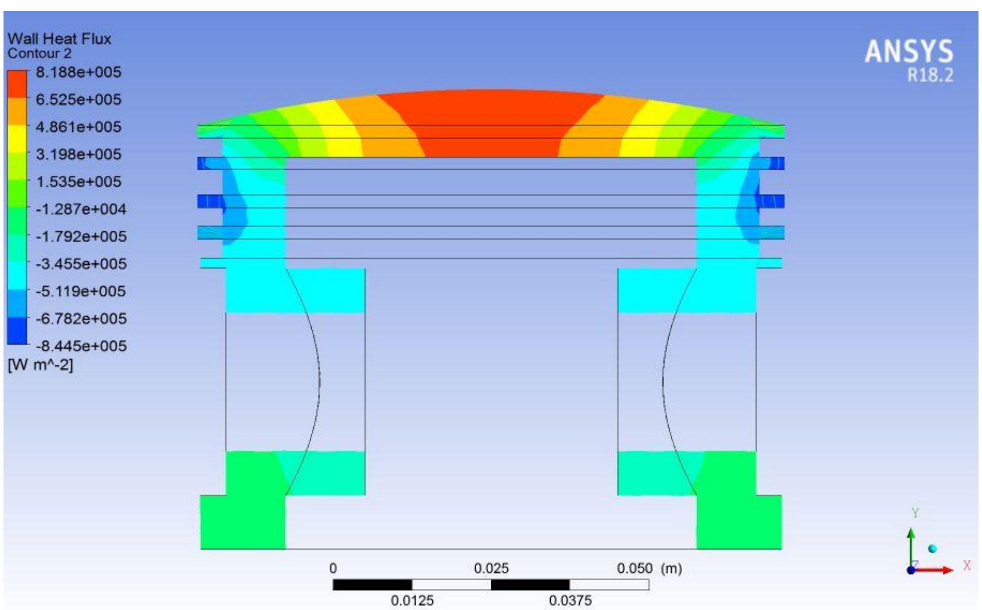

Fig.9 Wall heat flux of piston without thermal coating

7.2. Case 2A: Al-Si Piston with NiCrAl coating on piston crown of 1.5mm thickness

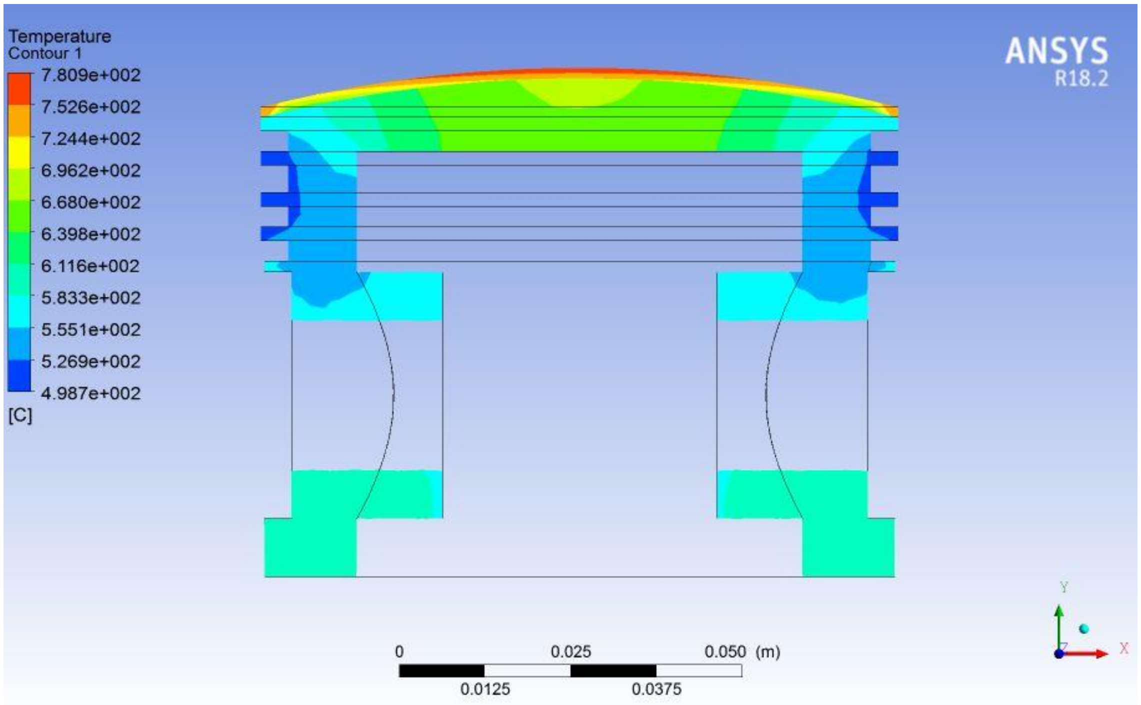

Fig.10 Temperature contour of piston with 1.5mm thickness NiCrAl coating

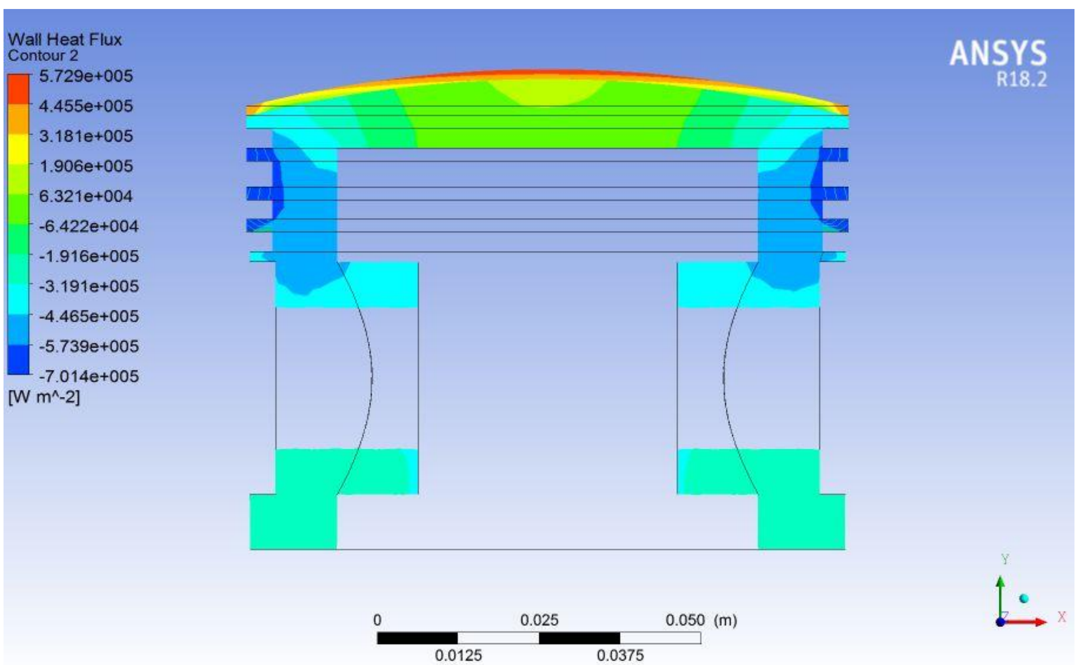

Fig.11 Wall heat flux of piston with 1.5mm thickness NiCrAl coating

7.3. Case 2B: Al-Si Piston with NiCrAl coating on piston crown of 2 mm thickness

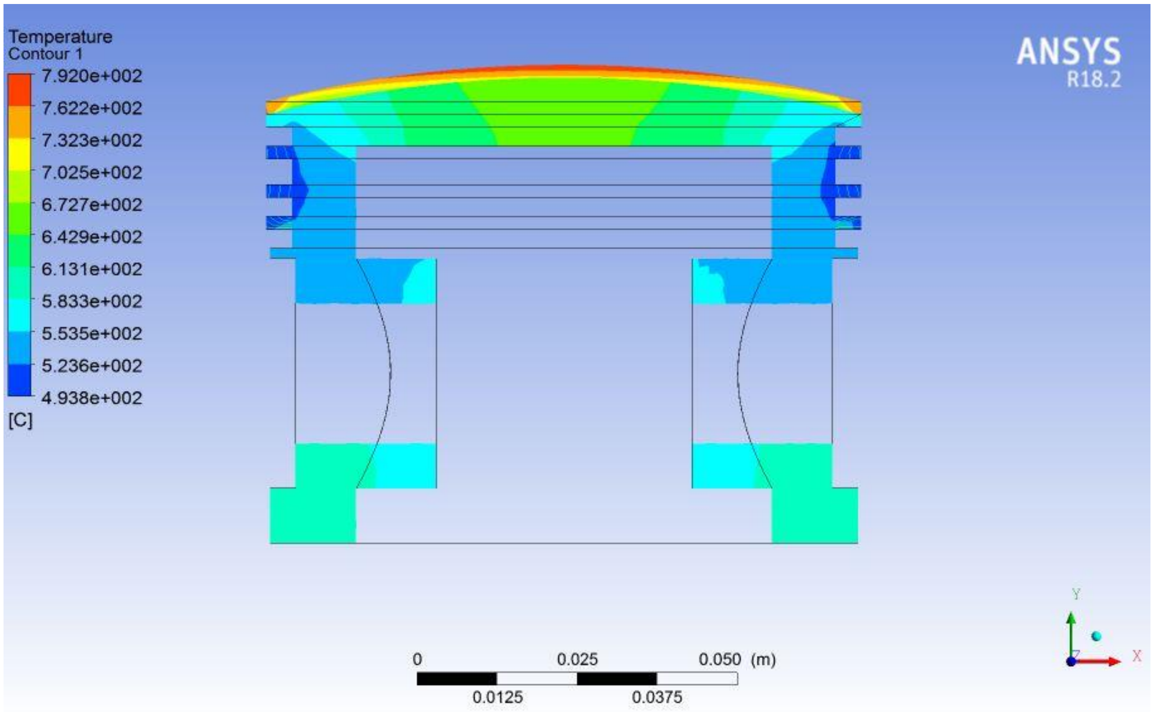

Fig 12 Temperature contour of piston with 2mm thickness NiCrAl coating

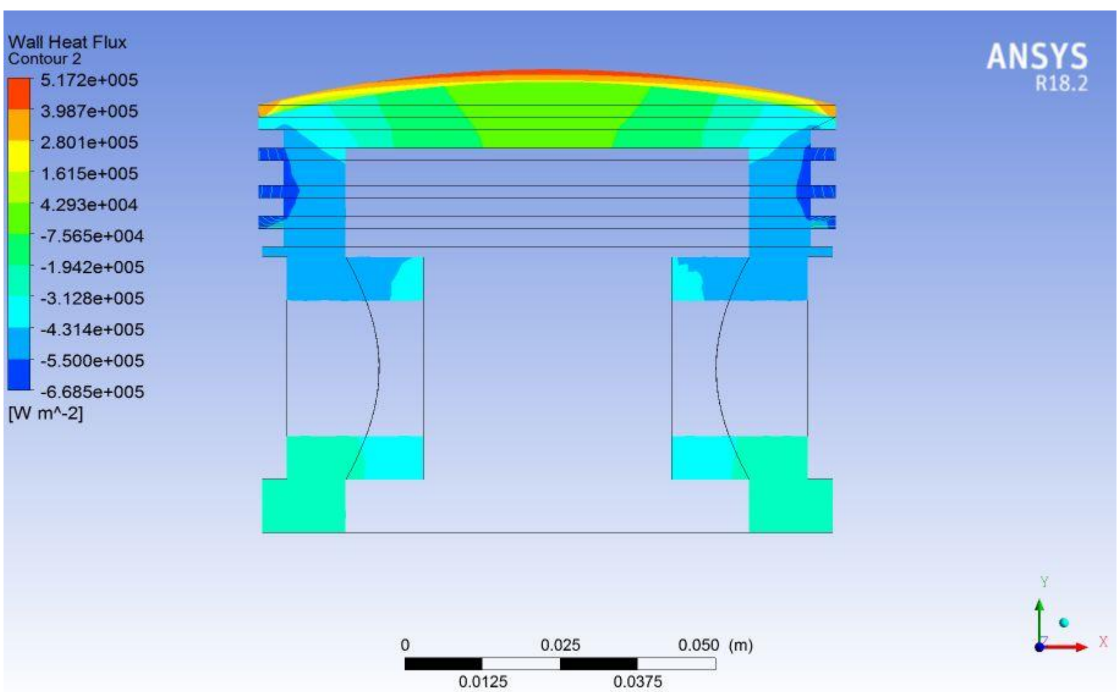

Fig.13 Wall heat flux of piston with 2mm thickness NiCrAl coating

7.4. Case 3A: Al-Si Piston with YPSZ coating on piston crown of 1.5 mm thickness

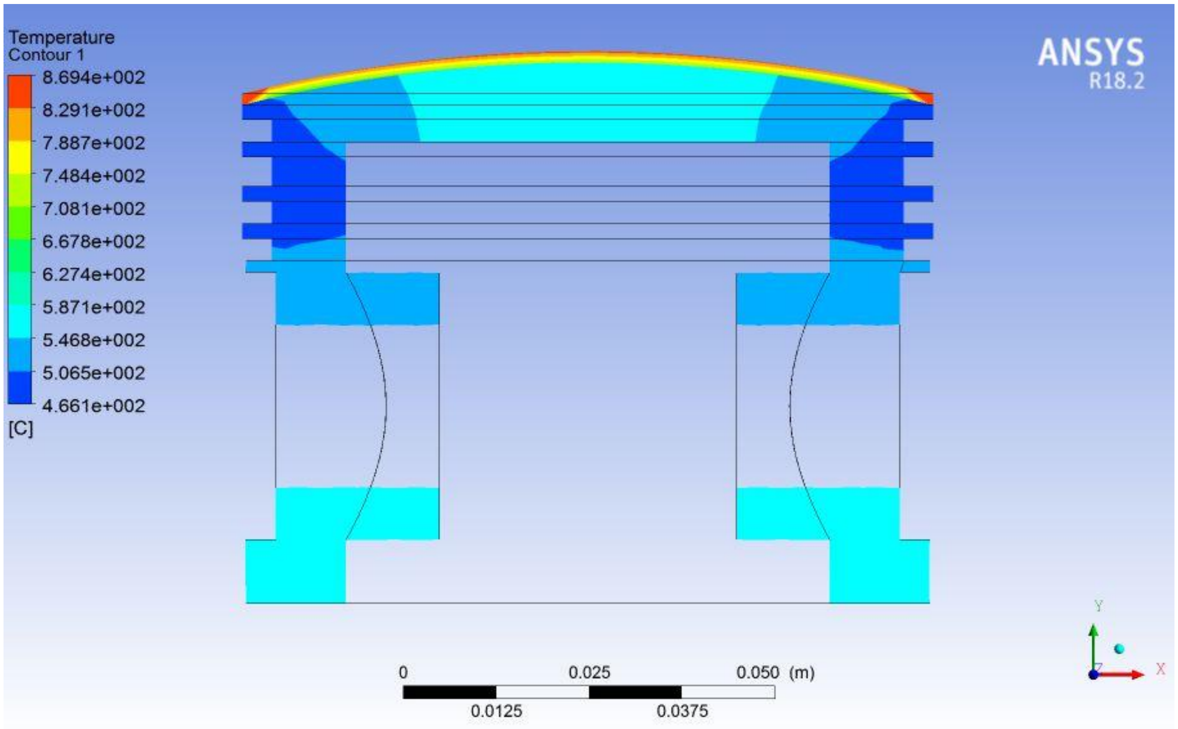

Fig. 14 Temperature contour of piston with 1.5mm thickness YPSZ coating

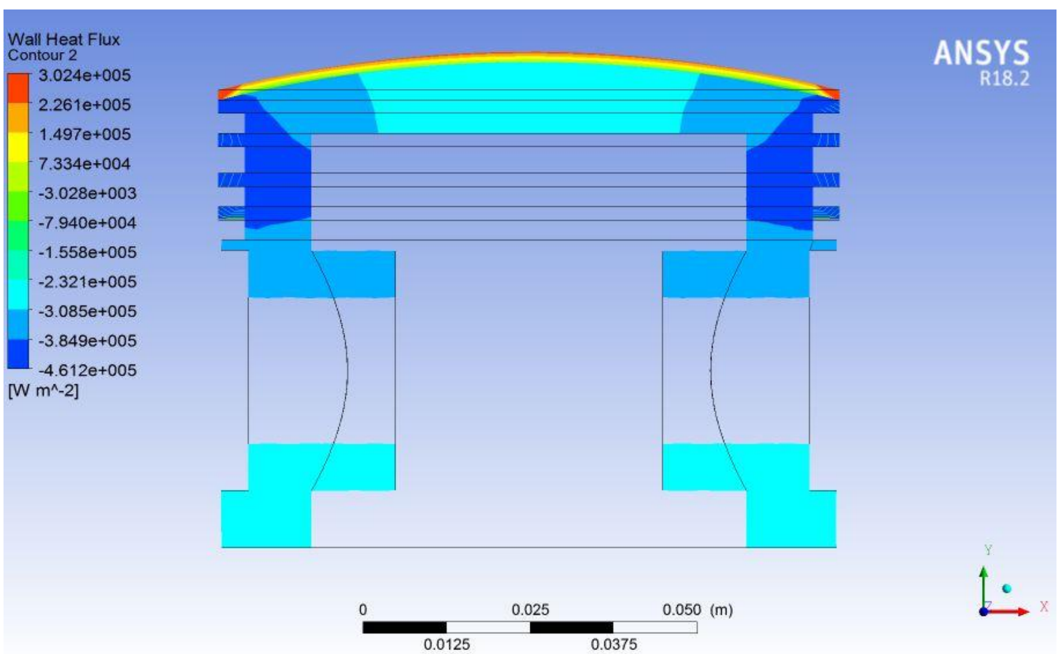

Fig. 15 Wall heat flux on piston with 1.5mm thickness YSPZ coating

7.5. Case 3B: Al-Si Piston with YPSZ coating on piston crown of 2 mm thickness

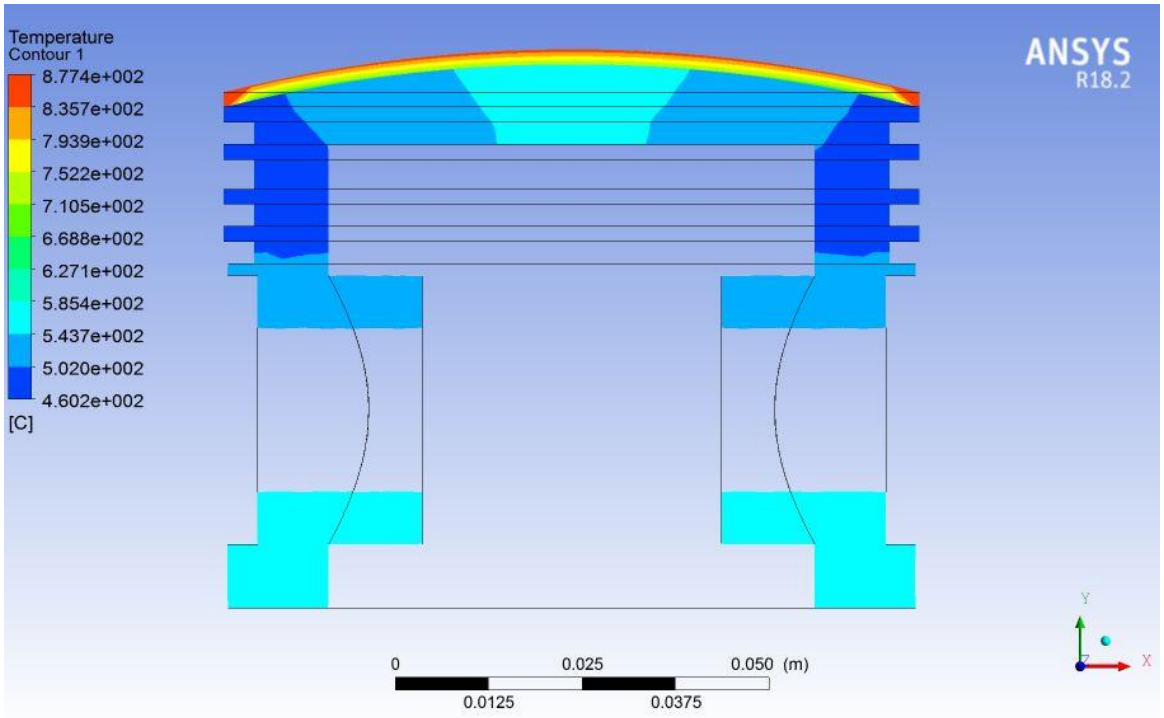

Fig.16 Temperature contour of piston with 2.mm thickness YSPZ coating

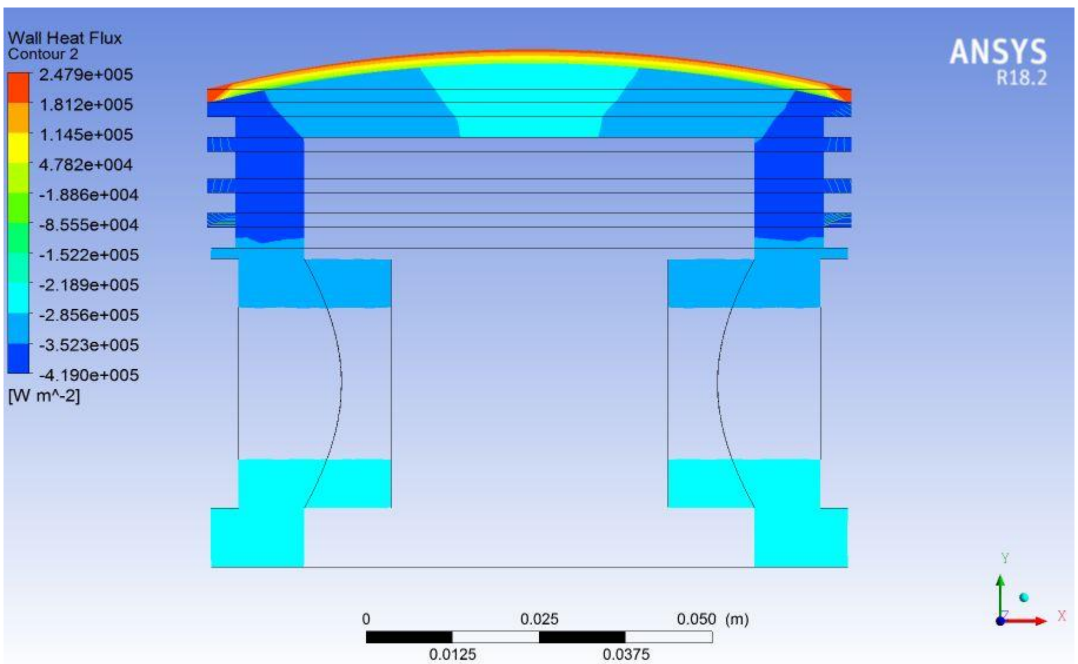

Fig.17 Wall heat flux of piston with 2 mm thickness YSPZ coating

7.6. Case 4A: Al-Si Piston with Ceramic (MgZrO3) on piston crown of 1.5 mm thickness

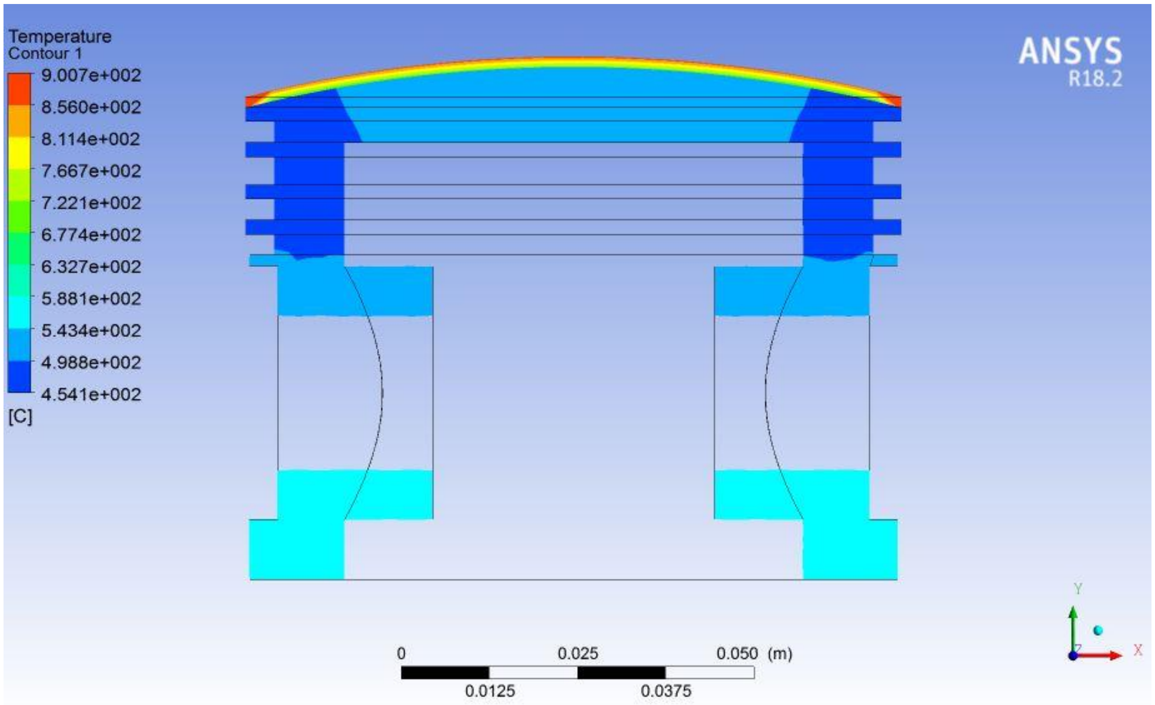

Fig.18 Temperature contour of piston with 1.5mm thickness Ceramic coating

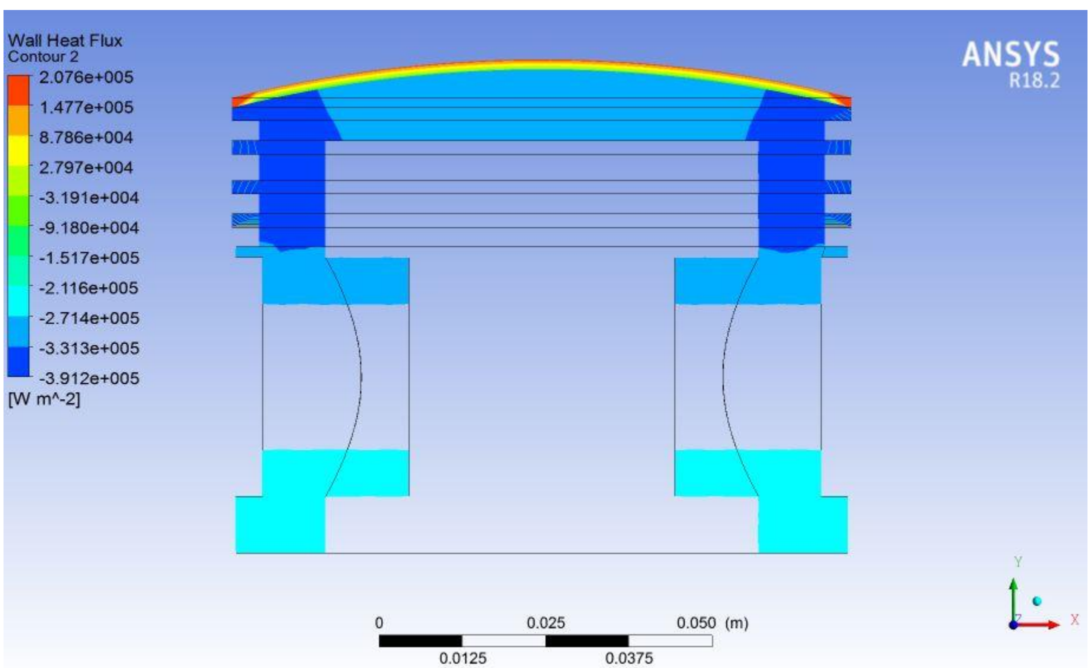

Fig.19 Wall heat flux of piston with 1.5mm thickness Ceramic coating

7.7. Case 4B: Al-Si Piston with Ceramic (MgZrO3) coating on piston crown of 2mm thickness

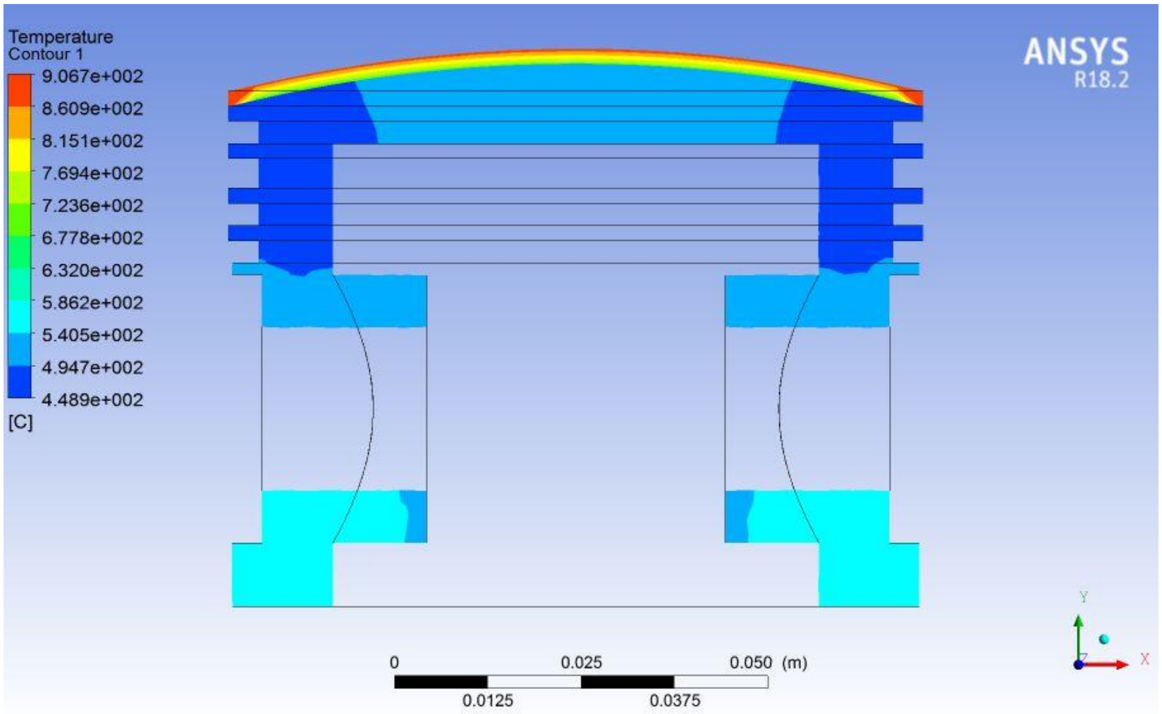

Fig.20 Temperature contour of piston with 2mm thickness Ceramic coating

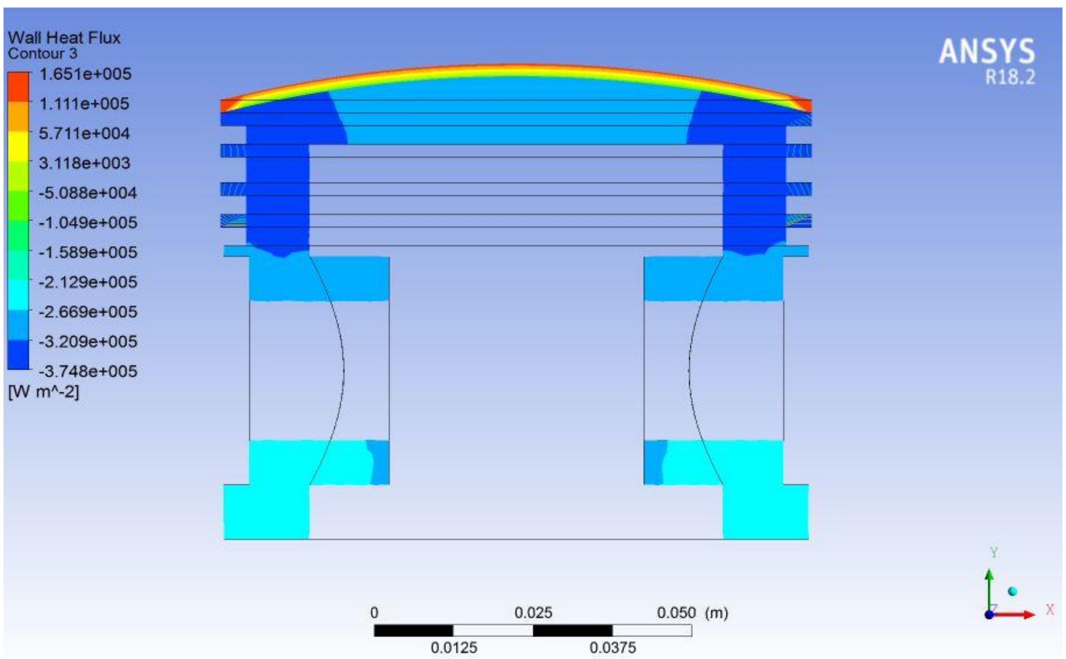

Fig.21 Wall heat flux of piston with 2 mm thickness Ceramic coating

8. RESULTS

S. No	Thermal Analysis Condition	Temperature ˚C		Heat Flux W/mm^2	
		Max	Min	Max	Min
1	Piston with no coating	739	518	8.18e5	-8.44e5
2	With 1.5mm NiCrAl Coating	780	498	5.72e5	-7.01e5
3	With 2mm NiCrAl Coating	792	493	5.17e5	-6.68e5
4	With 1.5mm YPSZ Coating	869	466	3.02e5	-4.61e5
5	With 2mmYPSZ Coating	877	460	2.47e5	-4.19e5
6	With 1.5 Ceramic(MgZrO3) Coating	900	454	2.07e5	-3.91e5
7	With 2 mm Ceramic(MgZrO3)Coating	906	448	1.61e5	-3.74e5

9. DISCUSSIONS

1. The above mentioned are the results for the thermal analysis done on piston under certain boundary conditions for with and without thermal barrier coatings. Used thermal barrier coatings are NiCrAl, YPSZ, Ceramic (MgZrO3) applied on piston crown having 1.5 mm. 2.0 mm thickness.
2. Our criteria are to resist or reduce the heat through piston due to hot gases on crown part such that the thermal loads in temperature form will be low. By doing this, the thermal loads can be reduced and life of piston can be improved.
3. By comparing without and with thermal coating, the piston with coating is suggested as suitable model as it resists the high temperatures due to heat
4. From temperature contours and corresponding values, the piston with thermal barrier coatings are reduced. Having 2mm thickness coating is more suitable for more heat resisting.
5. From wall flux contours and corresponding values, the flux value with ceramic coating with 2 mm thickness is appreciable.
6. As we increase the thickness of coating, the heat can be reduced further but the thickness has a limit as far as thickness is concerned because the mass gets added up.
7. For clear understanding, thickness limit to which it has to be applied, availability of coating in market, cost etc. parameters should be studied.

10. CONCLUSION

From the case study, it is clear that piston with Ceramic ($MgZrO_3$) type of thermal barrier coating with 2mm thickness applied on piston crown is most suitable model. Compared to all other cases, this piston model has got more life and performance also gets improves using this.

11. FUTURE SCOPE

1. Transient Analysis should be performed for better understanding as per reality
2. Analysis with exact thickness calculations of thermal coating can be done
3. Using temperatures from thermal analysis, mechanical static without time dependency, transient analysis with time dependency to find thermal stresses at weak locations can be performed.

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